AN INQUIRY

AS TO A MORE PERFECT FORM

OF

WATER-WHEEL

BY

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An Inquiry as to a More Perfect Form of Water-Wheel

A WATER-WHEEL is a wheel for applying the power of water to some useful purpose.

Water-power implies two things: a flow of water and a fall. We will express the former generally by the symbol q in cubic feet per second, the latter by h in feet.

Work is mechanical effect. It implies resistance overcome, and is conveniently represented by the raising of a weight. A pressure of 1 pound overcome through a distance of 1 foot is equivalent to the raising of a pound one foot and is called a foot-pound. 550 foot-pounds per second is a horsepower. The weight of a cubic foot of water at ordinary temperatures is very nearly $62\frac{1}{3}$ lbs. It varies slightly with the temperature, and will be here represented by the letter w. In computations relative to water-power, w is usually taken at 62.5 pounds. Another symbol of frequent use in hydraulic computations is the velocity imparted per second by gravity, designated by the letter g. This varies slightly with the latitude and altitude of the place.

Energy is capacity to perform work. A quantity q of water in a mill-pond, at a height h above the tail-water, has the energy $w\,q\,h$ foot-pounds, and it could exert that amount of energy if we neglect the losses incident to the application. A quantity q of water at the level of the tail-water, supposing it enclosed in a penstock communicating with the head-water, could exert upon a piston of 1 square foot cross-section the pressure $w\,h$ pounds, and could move the piston q feet, representing an amount of energy of $w\,q\,h$ foot-pounds. Energy in these forms is called potential energy, being the energy of position or the energy of pressure. When water, in the last named

case, issues from an orifice at or below the level of the tail-water, it takes a velocity, $v = \sqrt{2gh}$, and its energy is $wq\frac{v^2}{2g} = wqh$. This form of energy is called kinetic energy, or the energy of velocity.

Two remarks of importance may be here made as bearing on what follows: —

1. A head of water can exert a pressure or generate a velocity, but it cannot increase one of these effects without diminishing the other. When it has its full effect of pressure it can produce no velocity. When it has its full effect of velocity it can exert no pressure. This, of course, implies that the velocity is directly communicated

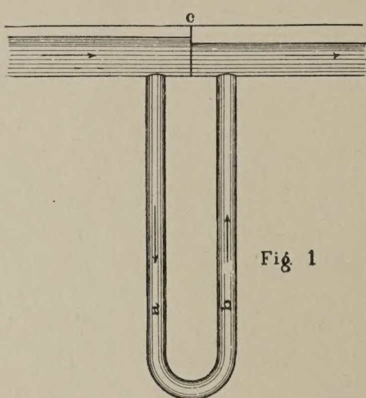


Fig. 1

by the pressure. Water under pressure may be put in motion by an extraneous cause without any effect upon the pressure.

2. The energy with which water leaves a hydraulic motor is a deduction from the efficiency of the motor.

The *efficiency* of a wheel is its energy as compared with the energy of the water acting on it.

A wheel which could raise the water that acts on it to the full height of the fall would have perfect efficiency in the organs by which it is acted on as well as in the organs by which it acts. We know this to be a mechanical impossibility, by reason of the natural resistances to motion. We should regard it as a very perfect apparatus that could perform this duty with an efficiency of 70 per cent. Nature, however, accomplishes the same result with an efficiency of more than 99 per cent. Consider the system of pipes represented in Fig. 1. Suppose the pipes a and b to be 20 feet in length. Water

goes down a and rises through b. The descent of the water in a may be regarded as the motive power; its elevation through b as the effect produced. A difference of one inch on opposite sides of the partition c will cause a perceptible current through the pipes. This machine acts with an efficiency of 99.6 per cent.

Water acts to turn a wheel in three ways: —

1. By weight.
2. By impulse.
3. By reaction.

The first is exemplified in the now nearly obsolete forms of overshot and breast wheels, which it is not our present purpose to discuss.

The action of water by impulse depends upon certain well-known mechanical principles. Force is required to impart velocity to water,

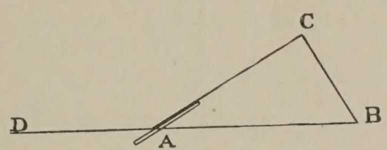


Fig. 2

and the velocity imparted is a correct measure of the force employed in imparting it. When water is in motion, force is required to change the direction or velocity of its motion, and the change of motion is a correct measure of the force. Suppose, for instance, a jet of water, moving from D toward B, in the line $D\,A\,B$. At A it encounters a smooth vane which so deflects it that it reaches C instead of B, at the end of one second, $A\,B$ representing the velocity of the jet, $B\,C$ is the change of motion occasioned by the vane. The effect of the vane is to impart to the water a velocity $B\,C$, and the pressure on the vane is in a direction parallel to $C\,B$. To find the pressure of the water on the vane, which is equal and opposite to that of the vane upon the water, we reason thus: —

Gravity acting freely for one second would impart to the water a velocity of g feet per second. The pressure of the vane acting for one second imparts to the water a velocity $B\,C$ per second. Therefore, the pressure on the vane is to the weight of water flowing in one second as $B\,C$ is to g. If a represents the cross-section of the stream, the weight of water is $w\,a\,v$, and the pressure is $w\,a\,v\,\dfrac{B\,C}{g}$

pounds. This is the pressure in the direction BC. To find the normal pressure we should use, instead of BC, its projection on a line perpendicular to the vane.

The impulse of water upon a stationary vane is attended with no material loss of energy. The water glides along the vane and glances off at the extremity, in a direction tangent to the latter, with substantially undiminished velocity. When the vane moves under the action of the water, a portion of the energy is imparted to the vane, and the energy of the stream is correspondingly diminished. It is manifest that if the energy of the stream is wholly imparted to the vane, it must leave the latter with no absolute velocity. That is, its velocity must be equal and opposite to that of the vane at the point of exit.

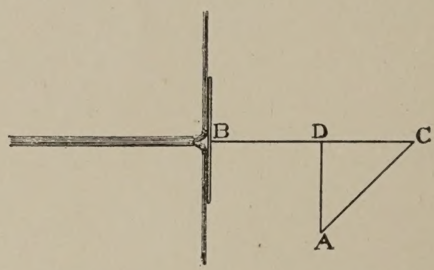


Fig. 3

Let us now consider the action of a jet on a flat vane perpendicular to its direction and moving in the same direction as the jet. In Fig. 3, let $BC = v$ represent the original direction and velocity of the jet, $BD = u$ the velocity of the vane. Were the vane not present, a particle of water at B would have reached C at the end of one second. By the action of the vane, the particle finds itself at the point A, at the end of one second, DA being $= v - u$. AC is the change of motion due to the action of the vane. The pressure on the vane, in a direction parallel to AC, is $w\,a\,v\,\frac{AC}{g}$. The change of motion normal to the vane is DC. The normal pressure on the vane is

$$P = w\,a\,v\,\frac{DC}{g} = w\,a\,v\,\frac{v-u}{g}. \qquad (1)$$

The energy imparted to the vane is

$$P\,u = w\,a\,v\,\frac{u\,(v-u)}{g}. \qquad (2)$$

This expression has its maximum value when $u = \frac{1}{2} v$, and becomes in that case

$$P u = \tfrac{1}{2} w a v \frac{v^2}{2 g} = \tfrac{1}{2} w a v h \qquad (3)$$

h being the head to which the velocity is due. In other words, the maximum energy that can be imparted to a flat vane normal to the stream is one-half that of the stream, or the maximum efficiency is 50 per cent, and the best velocity for such a vane is one-half that due the head.

There are two cases in which the energy becomes o, viz.:

1. When u is o, i.e. when the vane does not move. In that case,

Eq. 1 $$P = w a \frac{v^2}{g}. \qquad (4)$$

That is, the pressure on the vane is twice that of the head to which the velocity is due.

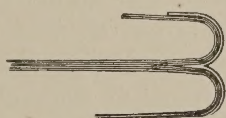


Fig. 4

2. When $u = v$, that is, when the velocity of the vane is equal to that of the stream.

A cup-shaped vane, Fig. 4, reverses the direction of the water's motion; so that if such a vane be moving in the direction of the stream with a velocity u, the change of motion will be $2\ (v - u)$.

$$P = w a v \frac{2\ (v - u)}{g}. \qquad (5)$$

And the energy exerted on the vane is

$$P u = w a v \frac{2\ u\ (v - u)}{g}. \qquad (6)$$

As before, the expression has its maximum value when $v = 2 u$, in which case

$$P u = w a v \frac{v^2}{2 g} = w a v h. \qquad (7)$$

Or the total energy of the stream is imparted to the vane, and the efficiency is 100 per cent. We have proceeded, however, upon assumptions which cannot be perfectly realized. In any practical application the direction of the water's motion cannot be exactly reversed, the vanes and their attachments cannot move without friction, the

water cannot approach and leave the vanes without velocity and consequent loss of head. The practical interpretation of this result is, that the arrangement described is consistent with the highest efficiency. Equation 5 shows that when the vane does not move, the pressure

$$P = 2\,w\,a\,\frac{v^2}{g} = 4\,w\,a\,\frac{v^2}{2\,g}. \qquad (8)$$

That is, the pressure on the vane is four times that of the head to which the velocity is due. As in the former case, the energy becomes o when $u = o$, and when $u = v$.

To trace the application of the above principles to different forms of vanes, and to vanes which do not move in the same line as the water, would be foreign to our present purpose, which is merely to put the reader in a position to understand what follows. We are, nevertheless, even now, in a position to notice two points of importance which are commonly lost sight of in the design of water-wheels: —

1. The purpose of the vanes or floats in an impulse wheel is to effect the greatest possible change in the motion of the water. Their length need be no greater than is necessary to accomplish that change.

2. It is a condition of the highest efficiency that the water should leave the vane with a velocity equal and opposite to that of the vane at the point of exit. Where the edge of the vane is radial to the wheel, different parts of it move with different velocities, and the fulfillment of this condition is impossible.

Reaction is the pressure exerted on the walls of a pipe or vessel from which water is discharged. Strictly speaking, the discharge of water from an orifice does not create pressure within the pipe or vessel from which it issues. It destroys the equilibrium of pressures previously existing. Suppose the pipe, Fig. 5, filled with water under pressure, and free to revolve around the center c. When the orifice o is closed, there is no tendency in the pipe to revolve. The water presses equally upon every part of the interior, and the force tending to turn it toward the right is exactly balanced by that tending to turn it toward the left. When the orifice o is opened, the conditions are changed. There is now a small space relieved of pressure on one side of the pipe, while the pressure acts in full force on the other side. The pipe will revolve around the center c in a direction opposite that of the stream.

In the arrangement indicated by Fig. 6, water issues from the orifice o and impinges upon a flat vane or plate P, which is in a line with the center c. The pipe in this case would have no tendency to revolve, as is evident from this consideration. In the arrangement of Fig. 5, the energy of the stream diminishes as the pipe revolves, u being the velocity of the orifice, and v that of the stream, the velocity relative to a fixed point will be $v - u$, and the energy of the stream $= \frac{(v-u)^2}{2g} w a v$. In the case of Fig. 6, the energy of the water will be $w a v \frac{v^2 + u^2}{2g}$. That is to say, the energy of the stream must increase if the system revolves; so that, instead of developing

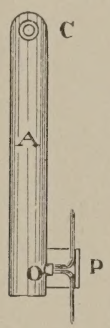


Fig. 6

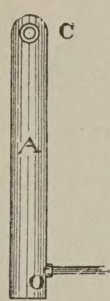


Fig. 5

energy, a constant expenditure of energy would be required to keep it in motion. We do not here consider the centrifugal force developed in the water when the pipe revolves. These considerations enable us to estimate the force of reaction. Since the system has no tendency to revolve, the reaction on the pipe must be exactly equal to the pressure on the vane. This we have already found equal to $2 w a h$. Let Fig. 7 represent the rim of a wheel containing the orifices $o\,o$, so disposed as to discharge water in a direction, as nearly as may be, tangential to the wheel. We assume for our present purpose that the direction is absolutely tangential. Let a, as before, represent the cross-section of the stream. The water is supposed to be at a greater pressure within the wheel than without, the difference of pressure being represented by the head h.

The best velocity of the circumference is that with which the water

issues, being the velocity due the head h. In this case, the absolute tangential velocity of the water leaving the wheel is o.

The energy imparted to the wheel is $2\,w\,a\,v\,h =$ twice the energy of the water under the given head.

This does not imply that the wheel is capable of yielding an efficiency of 200 per cent. In order that the water may issue from the orifices while the wheel is in motion, it must receive a tangential velocity equal to that of the wheel. To impart this velocity requires the energy $w\,a\,v\,h$. The wheel then, under the conditions supposed, is capable of exciting the energy

$$2\,w\,a\,v\,h - w\,a\,v\,h = w\,a\,v\,h$$

Fig. 7

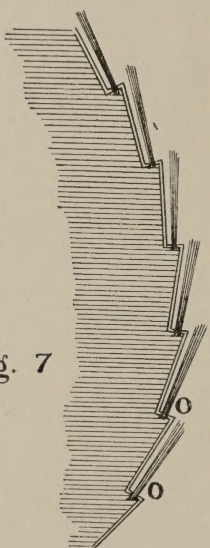
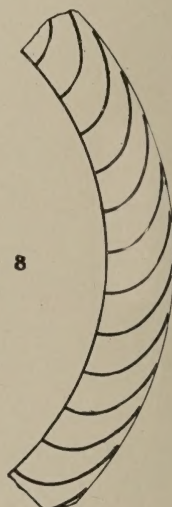


Fig 8



and from this must be deducted the several losses incident to motion, together with that due to the deviation of the issuing stream from the direction of a tangent.

In the above illustration of the principle of reaction no account is taken of the effect of the centrifugal force developed by the whirling motion of the water. The introduction of this element makes the problem more complex. The full effect of centrifugal force appears in the arrangement of Fig. 5, in which a pipe filled with water, under pressure, revolves around a center c, discharging from an orifice o, the entire mass of water being in rotation with uniform angular

velocity. This principle is demonstrated later on : — If we give the orifice o a velocity, $v = u = \sqrt{2\,g\,h}$, we develop at any point in the whirling mass of water a centrifugal force equal to the force represented by the head due the velocity at that point. The pressure acting on the orifice under this condition will be $2\,w\,a\,h$, and the velocity of the discharge will increase to $v = \sqrt{2\,g \times 2h} = 1.4143\sqrt{2\,g\,h}$. If we increase the velocity u of the orifice so as to make $u = 1.4143\sqrt{2\,g\,h}$, we develop a still greater centrifugal force, and so on. So that the condition of maximum efficiency $v = -u$ is impossible.

If, for example, we attempt to determine the value of u on the assumption that it is equal to the velocity with which the water issues from the orifice o, we should have the equation

$$u = \sqrt{2\,g\,(h + \frac{u^2}{2\,g})}$$

or $u^2 = 2\,g\,h + u^2$, which is only possible when $h = o$.

In the arrangement of Fig. 7 the entire mass of water is not set in motion with uniform angular velocity from the center outwards, and the pressure head developed by centrifugal force is less than that due the velocity of rotation. Suppose it to be represented by $m\frac{u^2}{2\,g}$, m being less than unity.

In this case

$$u \doteq \sqrt{2\,g\,(h + \frac{u^2}{2\,g})}$$

when $u^2 = 2\,g\,h + m\,u^2$ and

$$u = \sqrt{\frac{2\,g\,h}{1 - m}}$$

The fulfillment of the condition $v = -u$ would be possible in such a wheel, but u would be so great that the losses from friction and resistance to motion would exceed the waste of energy incident to a lower velocity.

A wheel of the form indicated at Fig. 8 would operate wholly by reaction. The water within the wheel would have a whirling motion, the tangential component of which is equal to the velocity of the inner circumference. We know this because otherwise the water could not enter the wheel. This whirling motion is not the direct effect of the head. It is imparted to the water mechanically by the

wheel. The pressure of the water does not diminish till the latter has entered the buckets. The energy of reaction exerted at the orifices of discharge exceeds the total energy due the head. This, as we have already seen, is partly absorbed in imparting the whirling motion to the water before it enters the wheel.

Impulse and Reaction Wheels. — Most wheels act partly by impulse and partly by reaction. In a wheel acting purely by impulse the water issues from orifices with the full velocity due the head and impinges upon vanes moving, preferably, with half that velocity. In a purely reaction wheel the work of the water is finished when it issues from the orifices of discharge. A tangential velocity equal to that of the influx orifice is imparted to the water, not directly by the head, but indirectly through the action of the wheel. Neglecting friction and losses incident to the movement of the water, the energy imparted to the wheel by the water is twice that due the head and quantity, but of this, one-half or more is useless energy, being that expended in imparting the necessary tangential movement to the water.

A wheel which has found many useful applications in cases of high head and small flow is the Pelton or hurdy-gurdy wheel. A jet of water acts upon cup-shaped vanes (Fig. 4) disposed around the circumference of the wheel. This is an impulse wheel pure and simple. The Barker Mill (Fig. 5) and the forms of Figs. 7 and 8 are reaction wheels pure and simple, observing that in 5 and 7 the orifices of influx and discharge are the same.

All wheels with guides may be regarded as acting partly by impulse and partly by reaction. The tangential velocity of influx is imparted directly by the head. The velocity of the efflux orifices is less than that due the head and greater than half the same. At full discharge they have more the character of reaction wheels. At diminished discharge they become impulse wheels.

Impulse and reaction wheels have this in common: Their efficiency depends upon the change which they effect in the direction of the water's motion, perfect efficiency implying exact reversal. Perfect efficiency also requires the water to leave the wheel with no tangential velocity, a condition inconsistent with radial orifices of discharge.

Centrifugal Force. — We shall have occasion in what follows to refer to certain propositions relative to the action of centrifugal force in the proposed form of wheel. I give in this place the demonstra-

tion of these propositions so far as required for our purpose. It is impossible to set forth and demonstrate these propositions without the aid of mathematical symbols and operations which are only intelligible to those who have studied that subject. Those who have not must ask the advice of those who have, or else take the results upon trust.

A cylindrical vessel, open at the top and partly filled with water, revolves around its vertical axis. What form will the surface assume?

Let Fig. 9 represent the vertical section of such a vessel.

The ordinates of any point o, in the curve, are $x = AD$ and $y = Do$; ω is the angular velocity. The surface must take such a form that the resultant of the forces acting at o will be normal to the surface.

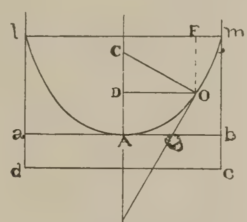


Fig. 9

The forces acting upon any given small mass, whose weight is w, at o, are: vertical w, horizontal $\frac{w}{g}\ \omega^2 y$. If we take y to represent the centrifugal force, i.e. the horizontal force, then $\frac{g}{\omega^2}$ will represent the vertical force, and the forces acting at o may be represented by $y = Do$, and $\frac{g}{\omega^2} = Fo = cD$. The resultant of these two forces will be represented by co, which must be normal to the surface. Now $\frac{g}{\omega^2} = cD$ is independent of the position of o. In other words, the subnormal is constant, which is a characteristic of the parabola. Any vertical section of the surface through the axis, therefore, is a parabola.

The equation of the parabola referred to its axis and vertex is ordinarily written,

$$y^2 = 2\,Px \qquad (9)$$

$2\,P$ being the value of x when $x = y$.

Differentiating (9) $2\,y\,d\,y = 2\,P\,d\,x$, whence $\frac{d\,y}{d\,x} = \frac{P}{y}$. The sub-normal is $y\,\frac{d\,y}{d\,x} = P$. Therefore $P = \frac{g}{\omega^2}$, and the equation of the curve may be put in the form

$$x = \frac{\omega^2\,y^2}{2\,g}. \tag{10}$$

$\omega^2\,y^2$ is the velocity of rotation at o; therefore, at any point in the vessel, the height of the surface above its lowest point is the height due the velocity of rotation.

The quantity of water in the cylinder remaining constant, and the cylinder being supposed of indefinite height, the rotation will not alter the aggregate pressure on the bottom, which is the weight of the liquid. The rotation will only alter the distribution of the pressure.

The question often arises, What is the pressure on the ends of a filled cylinder in rotation? Referring to Fig. 9, suppose, at the lowest point of the curved surface, a horizontal diaphragm $a\,b$ to be inserted, forming a closed cylindrical vessel $a\,b\,c\,d$. The pressure on both sides of the diaphragm will be equal, that is, the centrifugal force developed in the mass below the diaphragm will be exactly equal to the weight of water above it. The water will be the contents of the cylinder $l\,m\,b\,a$, less the contents of the paraboloid $l\,A\,m$. The volume of a paraboloid is one-half that of the circumscribing cylinder. The pressure on $a\,b$, therefore, is $\frac{1}{2}\,\pi\,w \times \overline{a\,A}^2 \times a\,l$. Putting r for the radius of the cylinder, the pressure on $a\,b$ is $\frac{1}{2}\,w\,\pi\,r^2\,\frac{\omega^2\,r^2}{2\,g}$, being the weight of a cylinder of water of radius r, and height equal to one-half the head due the velocity of the exterior circumference. It must be observed that the effect of atmospheric pressure is not here considered.

A vessel filled to the height H, the radius being r, is set in motion with the angular velocity ω. To find the highest and lowest points of the water.

The total volume of the water is $\pi\,r^2\,H$; ditto of the paraboloid, $\frac{1}{2}\,\pi\,r^2\,\frac{\omega^2\,r^2}{2\,g}$. Let $x =$ the height of the lowest point in the surface of water above the bottom of the vessel. Then $\pi\,r^2\left(x + \frac{1}{2}\,\frac{\omega^2\,r^2}{2\,g}\right) = \pi\,r^2\,H$, whence

$$x = H - \tfrac{1}{2}\frac{\omega^2 r^2}{2g}. \tag{11}$$

The highest point of the surface will be at a height $\frac{\omega^2 r^2}{2g}$ above the lowest point, or at a height $x + \frac{\omega^2 r^2}{2g}$ above the bottom. Its height above the bottom will be

$$= H + \tfrac{1}{2}\frac{\omega^2 r^2}{2g}. \tag{12}$$

Suppose the vessel $a\,b\,c\,d$ revolving around a horizontal axis, and it is required to find the pressure on the ends. We must remember that the centrifugal force developed in any particle of water is in no way affected by the direction of the axis of rotation, and will be the same as before. To this must be added the pressure due to the weight of the water in the cylinder. The surfaces on which the water acts are each πr^2. The average static head, in the horizontal position of the axis, is r. This part of the pressure will be $w \pi r^3$, and the total pressure

$$w \pi r^2 (r + \tfrac{1}{2} h) \tag{13}$$

h being the head due the velocity at the exterior circumference. The same result is obtained in a more direct manner, as follows. Put R for the exterior radius of the cylinder, and r for the distance, from the axis, of any point under consideration. The centrifugal force, at any point, is $\frac{w}{g}\omega^2 r$. This is the force with which a cubic foot of water pulls away from the center. The actual mass of water to which this applies is $w\,b\,2\pi r\,d\,r$, b being the axial length of the cylinder. The force per square foot is $\frac{w}{g}\frac{2\pi r\,b\,d\,r}{2\pi r\,b}\,\omega^2 r = \frac{w}{g}\,\omega^2 r\,d\,r$. This is the pressure which the particles at a distance r from the axis of rotation exert on all the surface outside of them. The end surface on which this pressure takes effect is $\pi(R^2 - r^2)$. The total pressure therefore due to centrifugal force is

$$\pi \frac{w}{g}\,\omega^2 \int_0^R r\,(R^2 - r^2)\,d\,r$$

$$= \pi \frac{w}{g}\,\omega^2 \left(\frac{R^4}{2} - \frac{R^4}{4}\right) = \tfrac{1}{2}\,w\,\pi\,R^2\,\frac{\omega^2 R^2}{2g} = \tfrac{1}{2}\,w\,A\,h,$$

where A is the area of the end of the cylinder.

Adding the pressure due to the weight of the water, we have for the total end pressure

$$w \pi R^2 (R + \tfrac{1}{2} h), \tag{14}$$

the same result as before, putting R in the place of r.

We are now prepared to consider the special question which will arise later, viz.: A cylindrical vessel in rotation, immersed in water, discharges water through a small orifice in its exterior circumference. What will be the pressure on the ends, from without inward?

First, suppose the axis of rotation vertical, and let d be the depth of water on the upper end of the cylinder. Let P be the pressure of the atmosphere in pounds per square foot. Then the total downward pressure on the upper end of the cylinder is $\pi r^2 (P + w d)$. The upward pressure per square foot at the outer circumference is $P + d w$, and at the center $P + d w - \frac{\omega^2 r^2}{2 g} w$. The pressure varies from the center outward, according to the parabolic law. The aggregate upward pressure is, therefore, $\pi r^2 (P + w d - w \frac{h}{2})$, h being the head due the velocity of the exterior circle, and the effective pressure acting downward is

$$= \tfrac{1}{2} \pi r^2 w h. \tag{15}$$

The effective upward pressure on the lower end will be the same, being increased by the pressure due to the height of the vessel, and diminished by the weight of water in the vessel.

Next, suppose the axis of rotation to be horizontal, and let d represent the depth of the axis below the surface of the water. The depth of the orifice, while in rotation, will vary from $d - r$ to $d + r$, its average depth being d.

The pressure per square foot directed inward will be $P + w d$, the aggregate pressure being $\pi r^2 (P + w d)$. The pressure directed outward will be $P + w d$ pounds per square foot at the circumference, and $P + w d - \frac{\omega^2 r^2}{2 g}$ at the center, the aggregate outward pressure being $\pi r^2 (P + w d - \frac{1}{2} w h)$. As before, the effective pressure tending to force the cylinder heads inward is $\frac{1}{2} \pi r^2 w h = \pi r^2 w \frac{h}{2}$; that is to say, the pressure represented by one-half the head due the velocity of the orifice. It appears that the orifice would play an important part in the pressure on such a revolving

cylinder. If open, the pressure represented by $\frac{h}{2}$ would act inward, if closed, outward. It is manifest that opening a larger orifice at the center of the cylinder would prevent the lowering of the pressure within the same, and have the same effect as closing the outer orifice, and the closing of the central orifice would have the same effect as opening the outer.

This result would not hold if the velocity were so great as to make

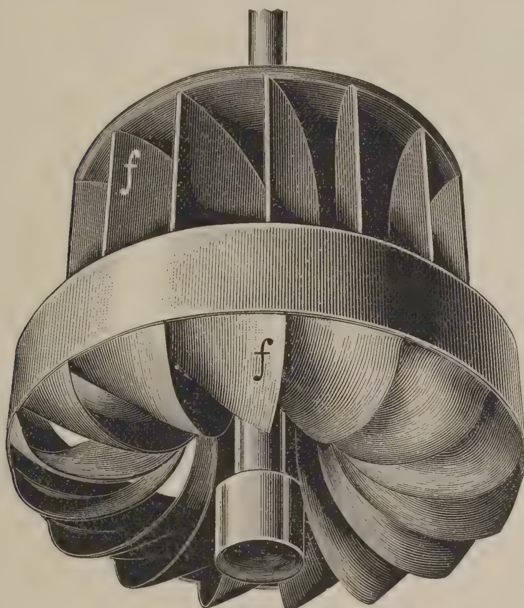


Fig. 10

h greater than the height due the atmospheric pressure increased by d, which would imply a vacuum at the center of the cylinder.

It is not the purpose of this little essay to enter into a general description of existing turbines. Some of their most prominent features, however, must be referred to in order to understand the advantages, if any, of the proposed form.

Floats. — Figures 10, 11 and 12 may be taken as types of the existing form of floats. In Fig. 10 the letter f below the band denotes the same float as f above. The water enters the wheel in a horizontal direction above the band and leaves it in an inclined

direction below. The orifices of discharge extend from the circumference nearly to the center. The same characteristics appear in 11 and 12. *a b*, Fig. 11, is the length of the orifice of discharge, in a radial direction. The length of the passage traversed by the water appears clearly in 12. These floats are at variance with both conditions of efficiency referred to on page 8. They present a longer passage to the water than is necessary for the required change of direction. The orifices of discharge are radial, and, in Fig. 10, the

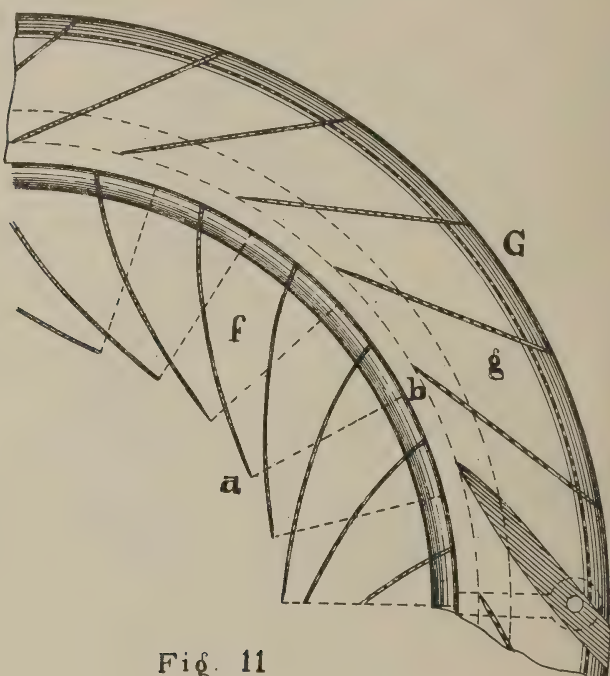


Fig. 11

inner end of the orifice moves with a velocity less than half that of the outer end; whereas, the velocity imparted to the water by the head acting on the wheel is substantially the same at the inner end as at the outer. The highest efficiency cannot be obtained from a wheel with floats of this form. The extent to which this form of float affects the efficiency at full gate is not wholly a matter of conjecture or theory. The Boyden-Fourneyron wheel (Figs. 13, 14 and 15), on the most rigorous trial, gave an efficiency of 88 per cent. The Swain wheel (Figs. 11, 12 and 16) has shown a maximum of

85. This falling off of 3 points must be charged to the form of the floats. Wheel No. 10 is still more faulty in this respect. At a competition test at Holyoke several years ago, where a large number of wheels were entered for trial, this wheel gave, as a maximum, not quite 83 per cent.

One maker of wheels — no doubt a very excellent mechanic and skillful man of affairs — says that the great power of his wheels "consists in the use of *long* buckets gradually leaning forward without any short or abrupt bend to prevent the natural flow or passage of water, and in turning the upper and outer half of the buckets forward in the direction the wheel runs, thus compelling the water that comes through the chutes to gather in largest bulk on the outer

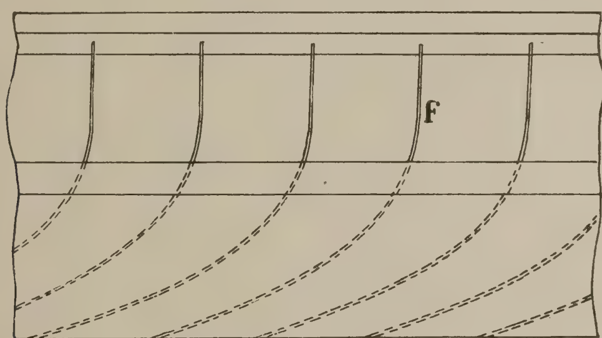


Fig. 12

parts of the buckets and therefore exert more pressure because pushing chiefly where there is most leverage." This quotation shows how loose and vague are the ideas of the action of water entertained by makers of wheels.

Guides. — Practically inseparable from every existing form of water-wheel are the guides for giving a suitable direction to the water entering the wheel. Figures 13 and 14 show these parts as applied to the Boyden-Fourneyron Turbine, in which the water flows from within outward. They consist, here, in a series of thin steel blades inserted in the disc and forming a series of narrow and deep channels. In addition to their function of guiding the water, they are attached, at their upper outer corners, to the supply pipe, and serve the purpose of firmly uniting this part with the disc, a purpose which

it would be impossible to secure in any other way without introducing parts that would interfere with the action of the water. It must be observed that the disc is an entirely indispensable part of the apparatus, serving to relieve the wheel and its bearings of the pressure of the water. In almost every form of center-vent wheel the guides sustain a plate through which the shaft passes in a stuffing-box and which serves to relieve the wheel of pressure. The point to

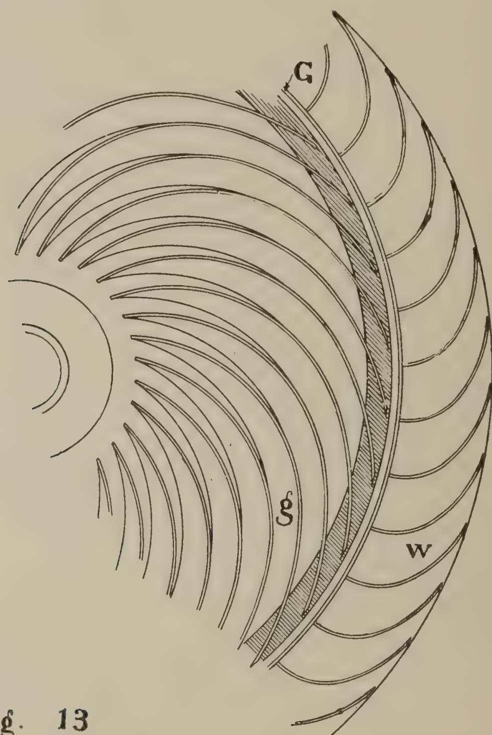


Fig. 13

which I wish to direct attention now, is this: The necessity of these parts to the structural solidity and strength of the wheel and case has diverted the attention of wheel-makers from the question: Are the guides necessary to the mechanical action of the wheel?

In a wheel whose design and construction is otherwise consistent with the highest efficiency, it is possible to so adjust the angle of the guides, the opening of the guides and the discharge orifices of the wheel as to secure, at full gate, a high degree of efficiency. Nearly the highest that any wheel admits of. This adjustment requires a

degree of knowledge of hydraulics that few men possess. But however complete this adjustment may be at full gate, it begins to be deranged as soon as the gate begins to close and, generally, when the discharge is diminished one-half, is wholly destroyed, and the efficiency much reduced. Wheels of the form shown in Figs. 13, 14 and 15 have shown, at full gate, the highest efficiency ever attained by a turbine. But observe how the conditions of efficiency are changed when the gate has descended to the position shown in Fig. 15. In this case, the water does not enter the wheel in the direction that the

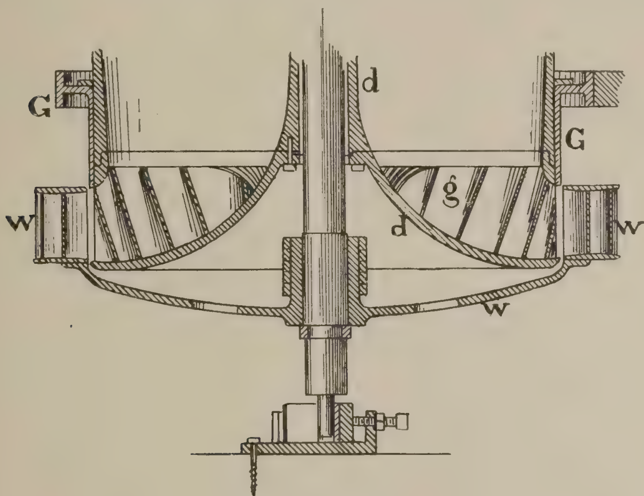


Fig. 14

guides would lead it. The opening formed by the gate and two consecutive guides is an orifice which the water approaches from various directions and from which it issues in a direction at right angles to the plane of the orifice, or radial to the wheel, at least tending to do so, and becoming so when the gate is nearly closed. The closing of the gate alters the direction of the water entering the wheel and so impairs its efficiency. But this is not the whole effect, nor the worst. The stream entering the bucket does not fill and pass smoothly through it as it does at full gate, but wastes its energy in commotions and eddies. It tends to fill the bucket at its exit, and so is discharged with a much lower velocity than it possessed at its entrance.

Here another remark might be offered as to the length of the passages through the wheel. These, as before observed, need be no longer than will suffice to impart the necessary change of direction to the water. At part gate the portion of the passage not filled by the stream is filled with dead water. The shorter the passage is, the less the stream mingles with the dead water, and the less the diminution of velocity sustained by it during its passage. The longer the passages are, the more the stream expands in its passage, and the lower (up to the point where the stream completely fills the passage) will be the velocity of discharge.

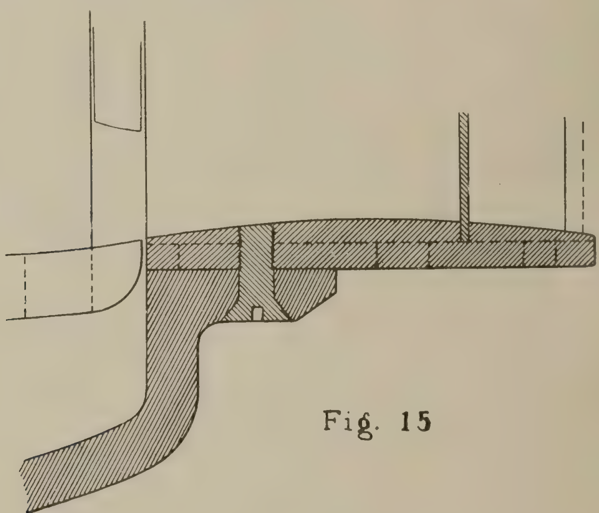


Fig. 15

This is the inherent and unavoidable defect of the turbine: That it cannot use a diminished quantity of water with the same efficiency as the full quantity that it is fitted to discharge. A wheel which shows an efficiency of 83 per cent at full discharge generally shows not above 65 at half discharge, and below half it is so low that makers do not usually care to publish it.

Nevertheless it is exceedingly desirable that water-wheels should be able to use a small quantity of water as efficiently as a large quantity. Streams vary constantly in flow. During several months in every year the flow of the stream is greatly below the capacity of the wheels. Steam is employed to make good the deficiency, and part gate is the normal condition of the wheels. It is extremely unfortunate that, at the period when water is the scarcest, it should

have to be used at a greatly diminished efficiency. The ability to work economically at $\frac{1}{2}$, $\frac{1}{4}$ or even $\frac{1}{8}$ of full power is just as desirable in a water-wheel as in a steam-engine.

Innumerable have been the devices for alleviating this defect. I would by no means attempt to describe or even name them. I will mention several of the most prominent.

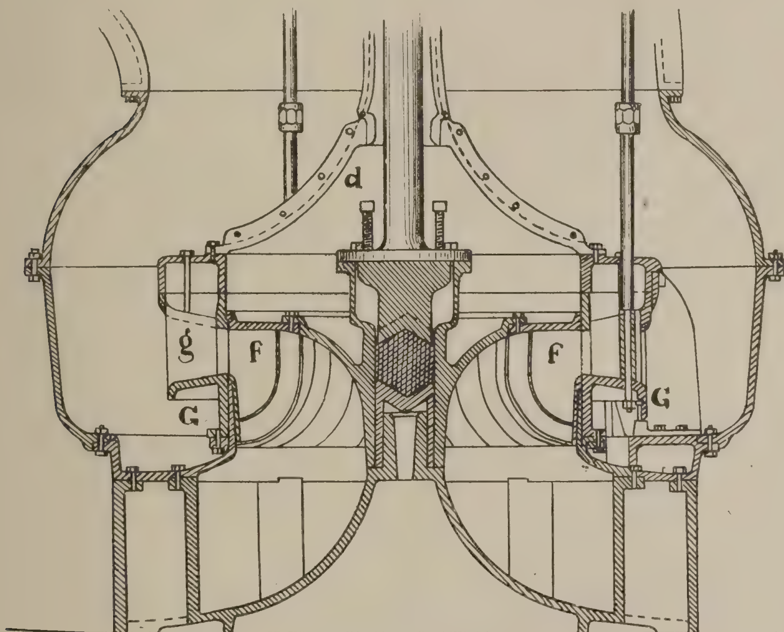


Fig. 16

1. In the wheel shown in Figures 13, 14 and 15, the guides have been given a sharp backward inclination, so as to stand at an angle of 45 degrees or less with the horizontal. In this arrangement a particle of water at the top of the guides, near the outer end, approaches the opening when the gate is low, not in a vertical, but in an inclined, direction, with a large component of tangential velocity. In a low position of the gate, however, the water does not reach the outlet of the guides with a sufficient velocity to overcome its tendency to issue in a radial direction. Moreover, this disposition does not affect the most serious source of loss, which is the tendency of the

water to fill the orifices of discharge from the wheel, and issue therefrom with a greatly diminished velocity.

2. In the wheel just referred to, several horizontal partitions have been introduced separating the wheel into a number of compartments, or "stories," to prevent the stream from expanding during its passage. This arrangement appears well calculated to diminish one source of loss incident to this form of wheel, but the results were not encouraging enough to lead to the extended adoption of this method. The tendency of the water to escape from the guides in a radial direction leads to losses of head which cannot be obviated by these means. In this condition of the wheel the guides cease to guide. Were the guides removed and the water allowed to enter the wheel entirely free from their control, there is reason to suppose that it would take a direction more conducive to efficiency.

3. In the Swain wheel (Figures 11, 12 and 16) the guides are attached to a broad flange in the gate G, which closes by rising. As the gate rises, the guides enter an annular chamber above, which diminishes the free height of the guide passages in the same degree that it diminishes the opening of the gate. This appears to largely obviate the loss arising from a change of direction in the water entering the wheel at part gate, and greatly improves its action. Tests of this wheel have shown an efficiency of 85 at full discharge, 60 to 70 at half, and some 45 at one-fourth of the full discharge. These results exceed any existing wheels on part gate, and are not inferior on full gate to any but that shown in Figures 13, 14 and 15, which has shown an authentic result of 88 per cent, and for which higher results have been claimed. The record of the Swain wheel, however, shows that there is still much to be desired in point of efficiency at part gate. It shows that this arrangement of gate does not obviate the second source of loss, viz. the expansion of the stream in traversing the buckets.

4. Fig. 17 represents another attempt to use large and small quantities of water with good efficiency in the same wheel. This is nothing less than a double wheel, with two sets of floats, two sets of guides, and two gates, all on the same shaft. The outer wheel $w\,w$ is governed by the cylindrical gate $G\,G$, which opens downward. The floats $f\,f$ and guides $g\,g$ belong to this wheel. The inner wheel $w'\,w'$ is controlled by the gate $G'\,G'$, opening upwards, and has the guides $g'\,g'$ and floats $f'\,f'$. In times of abundant water both gates are open. In lower stages the inner gate is closed, leaving the outer

one open. In still lower, the outer is closed and the inner is used. Or, these several dispositions are made not in accordance with the stage of the stream, but with the requirements of the mill.

This arrangement has the advantage that it fixes three different quantities of water which can be used with good effect, instead of one

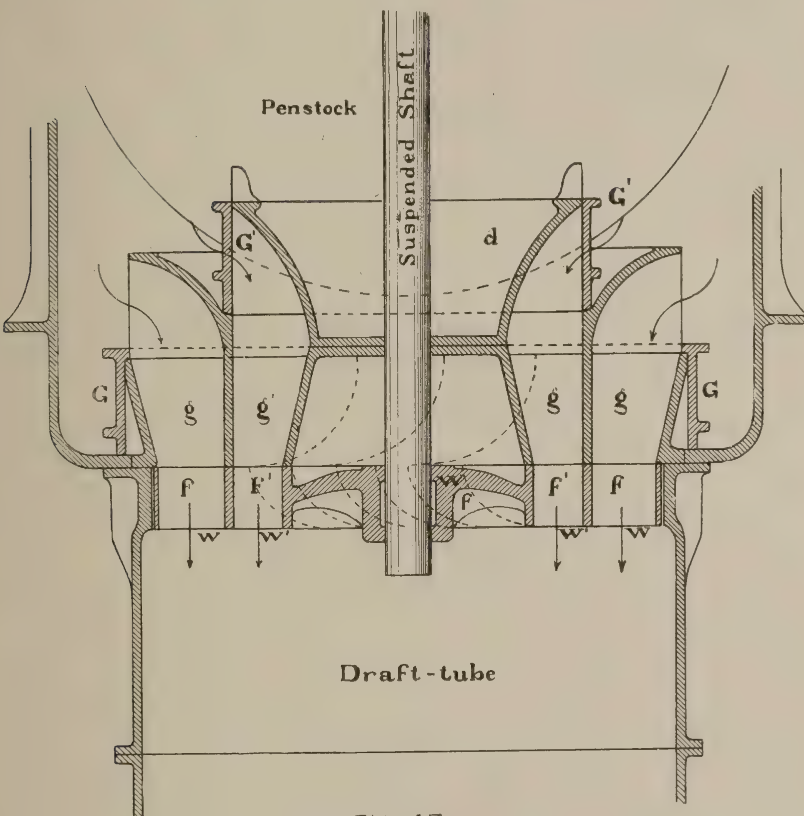


Fig. 17

as in the ordinary case. Any quantity between the capacity of both wheels and the capacity of the small wheel can be used with little loss. Below the latter quantity the defect appears in full force. The form of bucket adopted in this wheel, although of good efficiency at full gate, is one of the worst forms extant at part gate. However small the quantity of water admitted to the wheel, it is certain to issue in a uniform stream from the orifices of discharge with

greatly diminished velocity. This wheel is also liable to losses from which ordinary types are exempt. A turbine, in order to give its best effect, must run with a velocity which bears a certain ratio to that due the head. The connections must be such as to admit of this velocity when the shafting and machinery run at their normal speed. Two wheels of different diameter on the same shaft, cannot both run at this velocity. Moreover the wheel out of action is kept in rotation as a useless drag upon the other.

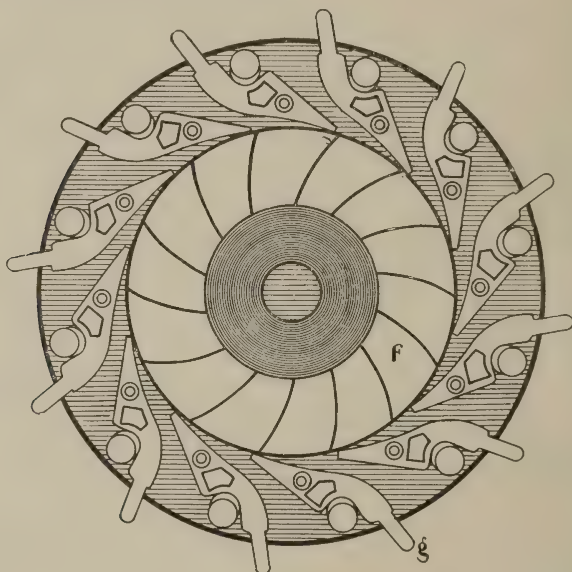


Fig. 18

5. In the forms of wheel shown in Figures 18 and 19, the guide serves the double purpose of guide and gate. It controls the width of the guide passages by turning upon a hinge or joint under the action of the regulator. In 18, the outer end of the guide is fixed; the inner end is susceptible of an outward movement, limited by the adjoining guide. In 19, the inner end is jointed, the outer end rotates. The passages are closed when each guide touches the adjoining guide.

The same remark may be made of this arrangement as of the Swain wheel. It obviates the loss incident to a change of direction and velocity of the entering water. But it in no way affects the second source of loss, viz. that arising from the expansion of the

stream in the wheel passages. To avoid this latter loss would require the wheel passages to be contracted in the same proportion as the guide passages, when the discharge is reduced.

From this brief survey of the present state of the art of wheel-building we are, I think, justified in asserting that no existing form of wheel is free from grave, inherent and unavoidable defects, defects which are material at full discharge, and become more and more marked as the discharge diminishes. No existing form is consistent

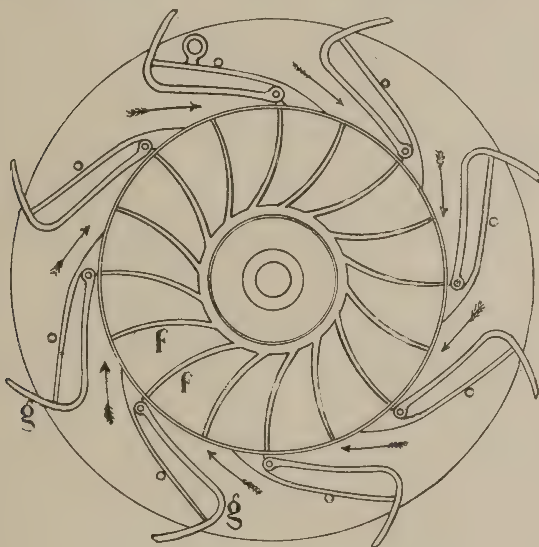


Fig. 19

in design with the highest degree of efficiency or with the well established principles of hydraulics.

They have resulted from tentative methods and from partial and incomplete knowledge, not from a thorough and comprehensive study of the whole subject.

It appears to me, also, that the only hope of developing a perfect water-wheel lies in a radical departure from existing forms, every one of which is intrinsically defective.

The whole subject of improvement turns upon this question: Are the guides necessary and indispensable to the efficient action of the wheel? I am convinced that they are not. It appears to me that in a wheel surrounded by a free space sufficient to allow the water to

move without constraint, it would naturally take the direction and velocity most conducive to the efficient action of the wheel. This, in a center-vent wheel, means a velocity, the tangential component of which is equal to the velocity of the exterior circumference of the wheel. What reason have we for supposing that the water will take that velocity?* We have the very simple and satisfactory reason that the water cannot otherwise enter the wheel. This answer, however, carries another question with it, viz.: Though there is no doubt that the water would take the required velocity, would not that movement be attended with serious loss of energy? I think not, for these reasons: —

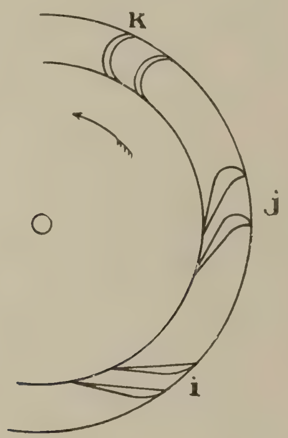


Fig. 20

1. When an orifice is opened for the escape of water under pressure, the water will approach the orifice. If the orifice recedes, the water will follow and overtake it.

2. A movement of rotation, under the conditions supposed, is in accordance with the natural tendency of the water. Water in a circular vessel, discharging through a central orifice, spontaneously takes a movement of rotation.†

* This would be true for an orifice opening normally, as *j*, Fig. 20, or backwards, as at *k*. It would not be true for an orifice opening toward the direction of rotation, as *i*. In that case, the water would be "scooped" into the wheel without taking the full velocity of the wheel.

† When a heavy particle (i.e. a particle having weight) moves freely under the action of a force directed toward a fixed point, the line joining it with the fixed point describes equal areas in equal times. This general proposition appears from Fig. 21. Suppose a

3. It is a universal principle of nature that every movement is performed with the minimum expenditure of energy. Water, in the case supposed, will enter the orifices of the wheel with the least loss of energy possible under the existing conditions. Now we know that if the water reaches the orifice with the rotatory velocity of the wheel, the loss of energy will be slight; and since we know that existing conditions admit of this velocity, and that the actual loss will be as small as is consistent with existing conditions, we are entitled to assume that the actual loss will be slight.

4. If we assume that the water enters the wheel with a less velocity than that of the floats, and suddenly acquires the motion of the latter, this sudden accession of velocity does not necessarily imply any loss of energy. Loss of energy may occur in several ways.

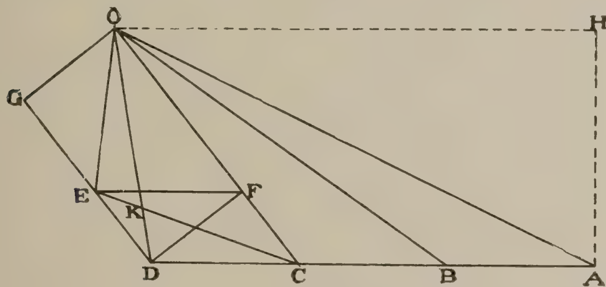


Fig. 21

heavy particle to move with uniform velocity in the line $A\,D$, — $A\,B$, $B\,C$, $C\,D$, being the equal distances moved in successive elements of time. Let O be any point whatever. The triangles $A\,O\,B$, $B\,O\,C$, $C\,O\,D$, are the areas described in equal times with reference to O. These triangles are all equal to each other, having equal bases and the common height $A\,H =$ the perpendicular distance of O from $A\,D$.

Now introduce the supposition that, at C, the particle is acted on by a force directed toward O, which would cause it to move a distance $C\,F$ in the element of time. At D draw $D\,G$, parallel to $C\,O$, and on it lay off $D\,E = C\,F$. Draw $C\,E$, then $C\,E\,O$ is the area described in the element of time under consideration. Join $E\,O$, and draw $O\,G$, perpendicular to $D\,G$. The triangle $C\,D\,E = O\,D\,E$, both having the base $D\,E$, and the common altitude $O\,G$.

The triangle $C\,E\,O = C\,D\,O - (C\,D\,E - D\,K\,E) + O\,D\,E - D\,K\,E = C\,D\,O$. Therefore, the areas described in successive elements of time are equal; and in order to make these areas equal, the velocity must increase as the particle approaches the fixed point. This is the law discovered by Kepler, and it governs the motions of the planets.

A particle of water in the wheel-case is under conditions very similar to those of a planet in free space. It enters the case with a certain velocity. As soon as it enters, it is acted on by a force directed toward a fixed point, i.e. the center of the wheel. It does not move straight toward the wheel, but circles around it with an increasing velocity.

One of these is the communication to the water of motions other than those necessary for its entrance into the wheel, i.e. useless movements. Commotions in water commonly arise from irregularities in the channels, or in the circumstances of movement. No such irregularity exists here. Loss of energy occurs when water passes orifices with contraction. No appreciable loss can occur here from that cause. The contraction, if any, is only that due to the radial component of the velocity, which is not over one-fifth of the tangential component. Each orifice of entrance has the contraction suppressed on one side, and it is rounded on two others. On the fourth side, contraction can only exist in virtue of the excess of the wheel's velocity over the tangential component of the water's velocity. Neither contraction nor commotion therefore can exist as a source of serious loss.

The most natural conception of the phenomenon is this : The water which has passed the tips of the floats is in motion with the full velocity of the wheel, the next outside film a little slower, the next slower still, etc., the acceleration being communicated by fluid friction. The loss of energy consists in the fact that, of two consecutive films of water, the one nearest the wheel moves a little faster than the one more remote, so that the energy expended is not fully represented by the velocity acquired. The energy represented by the velocity imparted to the film of water is not lost.

The loss, however, from fluid friction in this wheel is no greater than in any wheel of equal surface (speaking now of the general surface of the wheel, not that containing the orifices) and equal velocity. In any wheel, the film in contact with the wheel moves with the velocity of the wheel, the adjoining film a little slower, the next slower still, etc., precisely as in this.

I have, therefore, become convinced that the guides, although in existing forms of wheel, necessary for constructive reasons, are in no sense essential to the efficient action of the wheel. That they are attempts to force upon the water a direction and velocity which it would take spontaneously if relieved of constraint. That, ordinarily, they but imperfectly fulfill their purpose at full gate, and are a prolific source of waste at part gate. The first step in the improvement of the water-wheel, therefore, is, as it appears to me, to dispense with the guides, and to adopt a form of wheel that does not require them for constructive reasons.

The second essential to the perfect action of the water is a gate

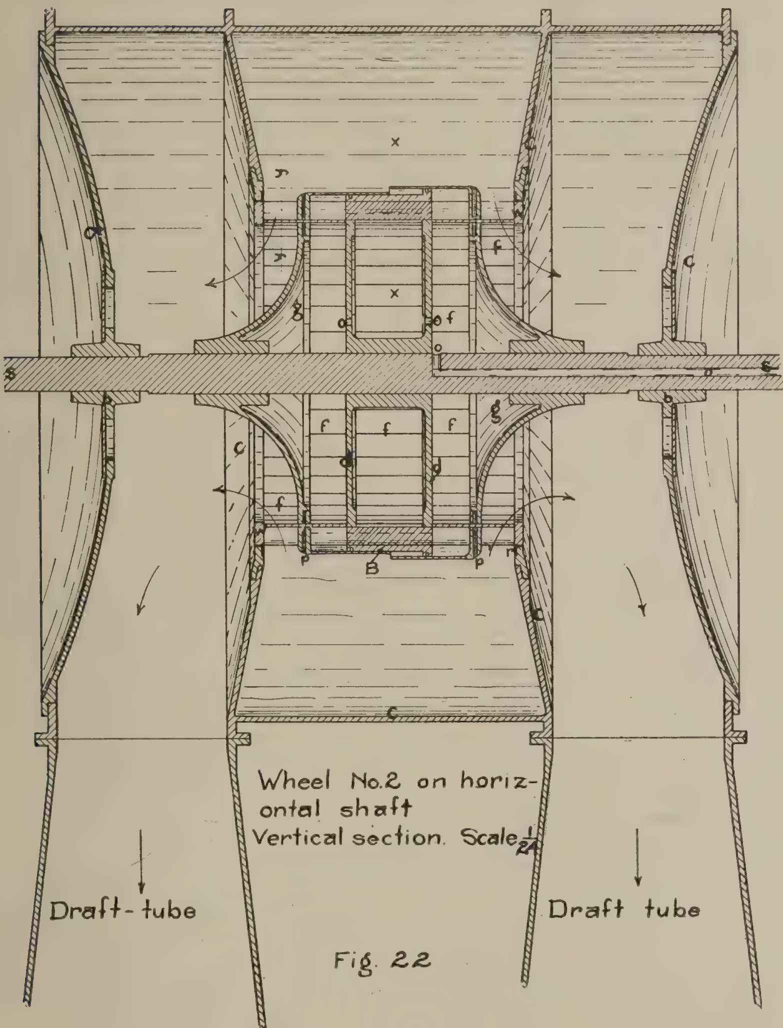
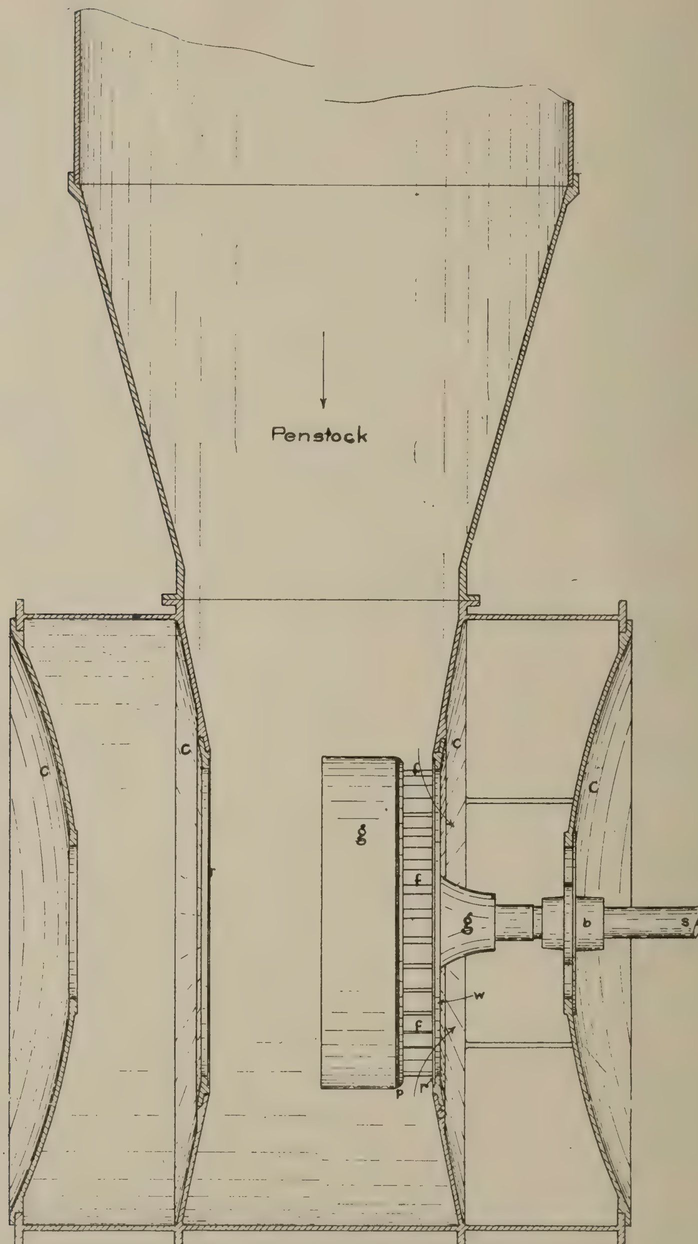


Fig. 22

that shall, in closing, contract not only the influx of the wheel, but the entire passages through it.

The attainment of these conditions necessitates an abrupt and radical departure from all existing forms of water-wheel.

The figures which follow illustrate my idea of a form of water-wheel calculated to obviate all the above described defects. It must

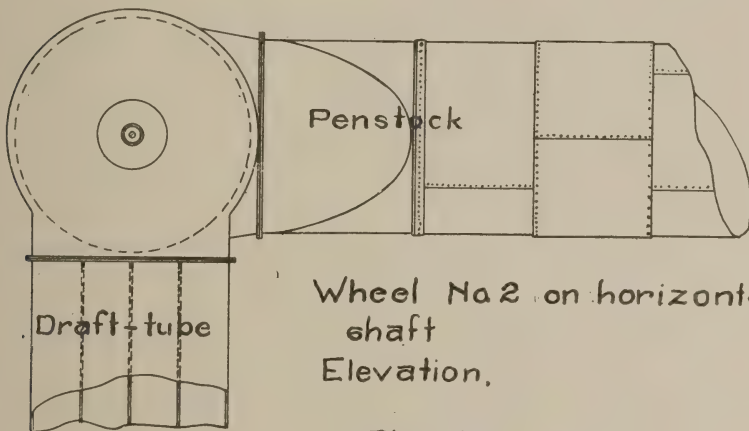


Wheel No 2 on horizontal shaft
Sectional plan - half, looking up, and half, looking down.

Fig. 23

be observed that these are, in no sense, working drawings. They are intended to exhibit the principles on which such a wheel could be constructed, and are sufficiently detailed to show that the construction of such a wheel involves no mechanical impossibility, and is entirely within the resources of modern engineering.

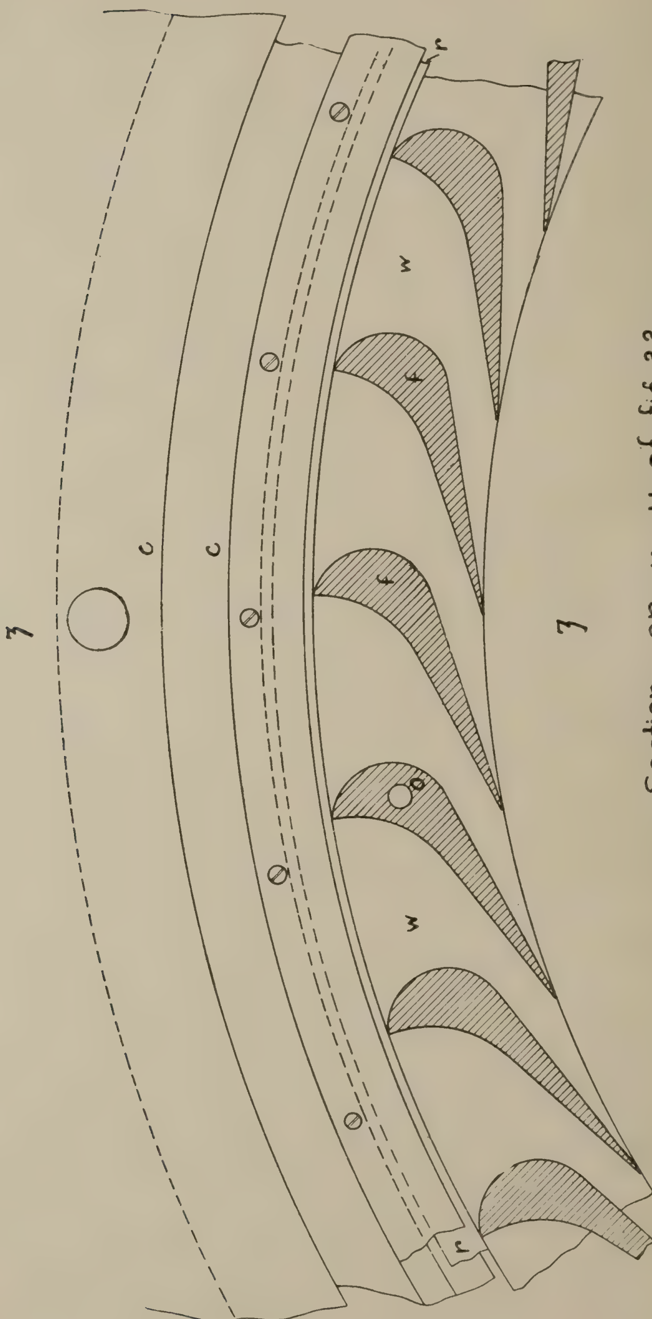
Fig. 25 shows the form of the floats and float passages, Figs. 22 and 23 the form of the gate. The gate *g* is a conoidal disc with a central hub, which slides on the shaft. A heavy hub, secured to the shaft, carries the flat disc or discs *d d*, to which the floats *f* are secured.



Wheel No 2 on horizontal shaft
Elevation.

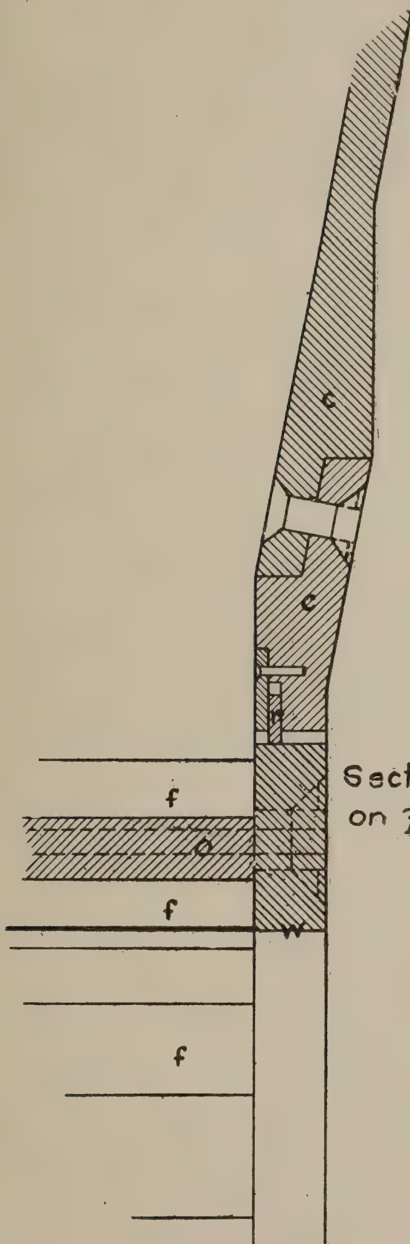
Fig. 24

The outer part of the gate is provided with openings through which the floats pass. These openings admit of being packed as indicated at Fig. 28. Stout rims are attached to the outer ends of the floats in the manner to be described later. The water approaches the wheel from the exterior with a revolving motion. Its rotatory velocity at its entrance to the wheel is equal to the velocity of the exterior circumference. If this was not so, the water would not enter the weeel. It is discharged in the reverse direction with a velocity nearly equal to that due the head. Its entrance to the moving orifices of the wheel implies no greater shock or loss of head than would be involved in its entrance to rounded stationary orifices. It passes the wheel under conditions consistent with maximum efficiency. These conditions are in no way changed by the opening or closing of the gate. The energy of the water in this wheel is developed wholly by reaction. It is, as shown at page 10, nearly double



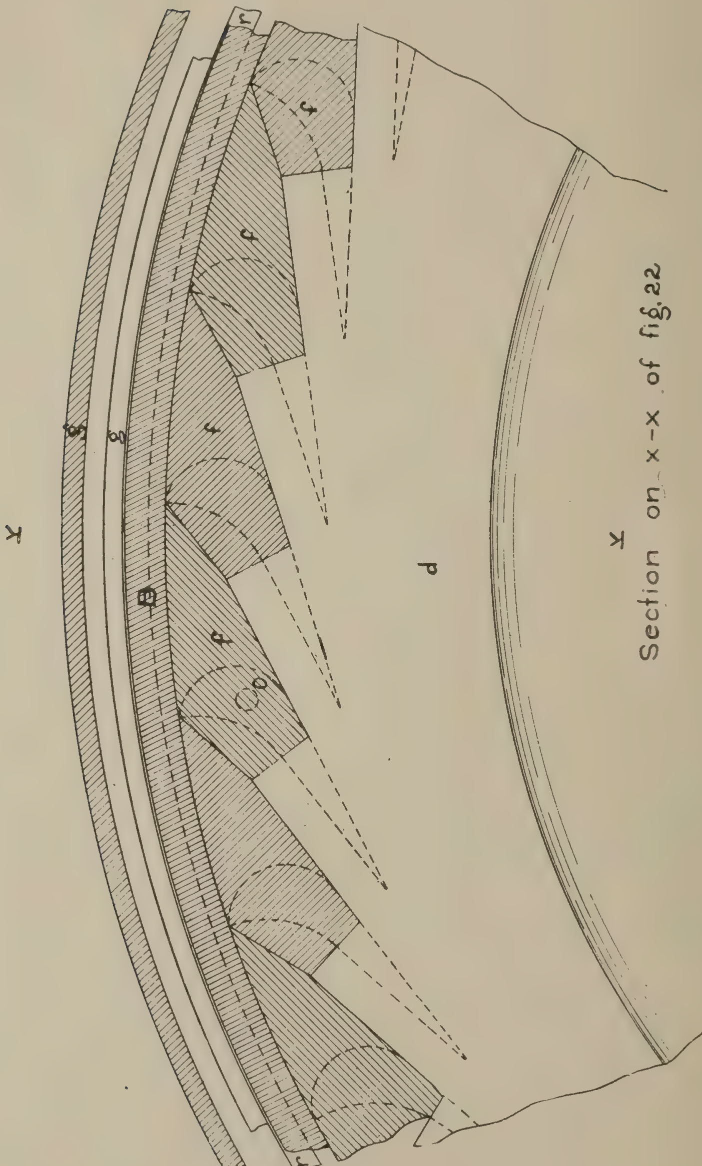
Section on y y of fig 22

Fig. 25



Section of fig. 25
on 7-7

Fig. 26



Section on x-x of fig. 22

Fig. 27

that due to the head and quantity of water; but half of this energy is absorbed in the work of imparting the whirling movement to the water before or during its entrance to the wheel.

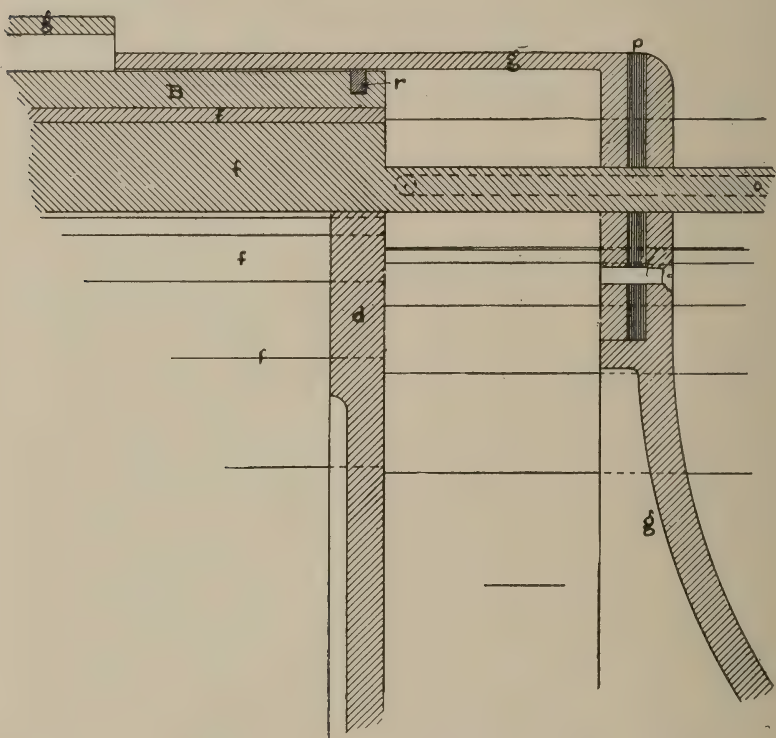
We will now describe the construction of the wheel and its adjuncts. Figs. 22 to 28 relate to a wheel on a horizontal shaft.

The Gate is in two parts: — The first part is a disc of conoidal shape which slides horizontally upon the shaft; the second is a cylinder with a broad internal flange, as shown at Fig. 28. Both parts are pierced with openings for the passage of the floats. At the junction of the two parts is a thick sheet of fibrous packing, pierced in like manner. This being compressed by the screws which fasten the two parts together packs the floats. The cylindrical part of the gate has the packing ring *r*, so that, in a single wheel, the space between the gate and disc, in a double wheel the space between the two gates, becomes a water-tight compartment. It would be a very simple matter, also, to introduce packing at the hub where it slides on the shaft.

The Discs. — The wheel under consideration is a double wheel. The central hub which is fastened to the shaft carries two flat circular discs. These have openings, *o*, which allow the water to pass freely. The rim of the disc is thickened and notched like a ratchet wheel, as shown at Fig. 27.

The Floats. — These are continuous through both wheels. The part traversed by the gate is of the form shown in section, Fig. 25. The part resting on the discs, and lying between them, has the section shown by the cross natching in Fig. 27, the blade of the float coming to a close shoulder against the disc, and preventing any tendency to endlong displacement. After being put in place and temporarily fastened, the wheel is put in a lathe, and the central part of the floats turned off smoothly, leaving the diameter of that part of the wheel a little greater than that of the outer ends of the floats. Then a heavy band, *B*, is shrunk on. Fig. 28 shows this band extending over the whole space covered by the discs, but two narrower bands would do as well. The float may have a thickness of $1\frac{1}{2}$ inches near its outer edge, forming a very strong stiff bar. The outer end of the float is turned down to a cylindrical stud, $1\frac{1}{4}$ inches diameter, and $1\frac{1}{2}$ inches long, and threaded. Some 4 of the floats in a wheel are bored longitudinally with holes, *o*, Figures 25, 26 and 28. These holes reach from the outer end to the disc, and are there met by holes cut from the outside of the float. These holes connect the interior of the wheel with the low pressure compartment of the case. The band, *B*, is thicker at one disc than the other to allow the cylindrical parts of the gates to telescope when open. A groove is turned in

the band, at each disc, for the packing ring *r*. After shrinking on and finishing the bands, the cylindrical part of the gate is put on, the flange straddling the floats. Then the sheet of fibrous packing is slipped on. Then the discoidal part of the gate is adjusted, and the screws turned up which connect the two parts and compress the



Section on k-k of fig 27

Fig. 28

packing. Then the rim, which is bored to receive the threaded studs on the outer ends of the floats, is put in place and solidly fastened by countersunk nuts.

The Shaft has an internal bore-hole communicating with the interior of the wheel. At the end of the shaft this bore-hole communicates with a pipe by a stuffing-box.

The Case. — The wheel being set above the level of the canal of discharge, the case has high pressure and low pressure compartments. The case is shown in Figures 22, 23 and 24. It is a short cylinder of cast iron with flanges for the attachment of the penstock and draft tubes. The interior compartment is in communication, by means of the penstock, with the upper level of the mill site. Being exposed to a bursting pressure, it is formed by two conical diaphragms joining the large cylinder. The junction is marked by two broad ribs running around the latter and widening into flanges for the attachment of the penstock and draft tubes. An annular portion of these diaphragms, next the wheel, is made detachable for convenience of finishing. Ribs also run around the ends of the exterior cylinder, and expand into flanges for the attachment of the draft tubes. The pressure on the ends of the cylinder is inward, and these ends are of dish shape, bending inward. This form not only gives great strength to resist the pressure, but shortens the unsupported part of the shaft. The flattened portion of the penstock, at its junction with the case, can be strengthened by external ribs, if required. The draft tubes being rectangular in section are divided by partitions into several distinct passages, as shown in Fig. 24, for greater strength. As the rim *w*, of the wheel, Fig. 26, must revolve without touching the case *c*, an annular space must exist, allowing for wear and imperfection of workmanship, through which the escape of water would be objectionable. To alleviate this difficulty, the small ring, *r*, is confined to a seat turned on the case so as to be capable of slight lateral movement. This ring can fit the rim of the wheel much closer than the fixed case, while yielding to any slight displacement of the wheel, from wear or other cause.

The Bearing, *b*, of the shaft, is an undivided cylinder. It has a rib or flange around the middle by which it is riveted to a circular plate of wrought iron. This latter is fastened, at its outer circumference, to the end plate of the case, covering a circular opening in the same, some 30 or 36 inches in diameter. The bearing has an oil-cup and a packing gland not shown. This bearing, I presume, will be the subject of some criticism, but I think it a correct design. Bearings are usually made in two halves, for convenience in setting up machinery rather than any inherent advantage in that method. The ring of boiler plate surrounding the bearing gives it a slight but sufficient degree of flexibility, which is favorable to uniform wear. The pressure being from without inward favors the admission of oil. The

admission of water to a bearing which is well lubricated is no disadvantage, as is shown in the Westinghouse engine, where the bearings run constantly in water covered with oil.

Regulation. — Fig. 29 is a schematic sketch of the proposed regulator, and Fig. 30, a section of the valve for controlling the movement of water through the central bore-hole in the shaft. The plug of the valve carries an arm resting on the spindle of the regulator,

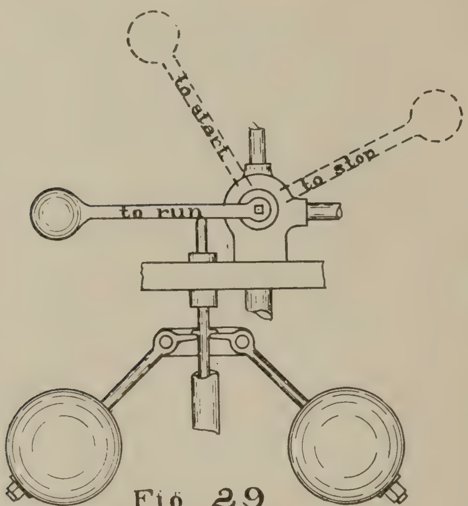


Fig. 29

Sketch of governor and section of valve to regulate speed of wheel

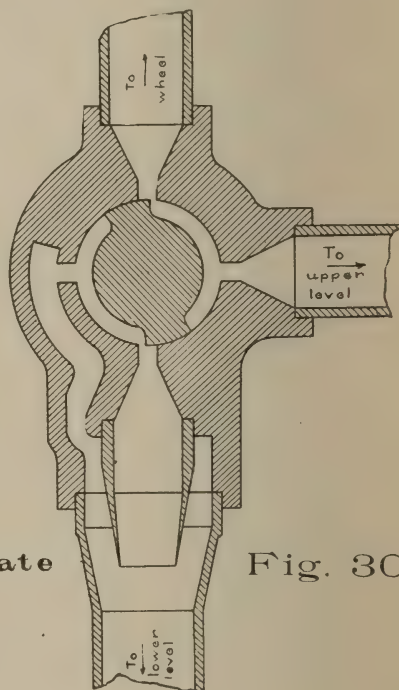
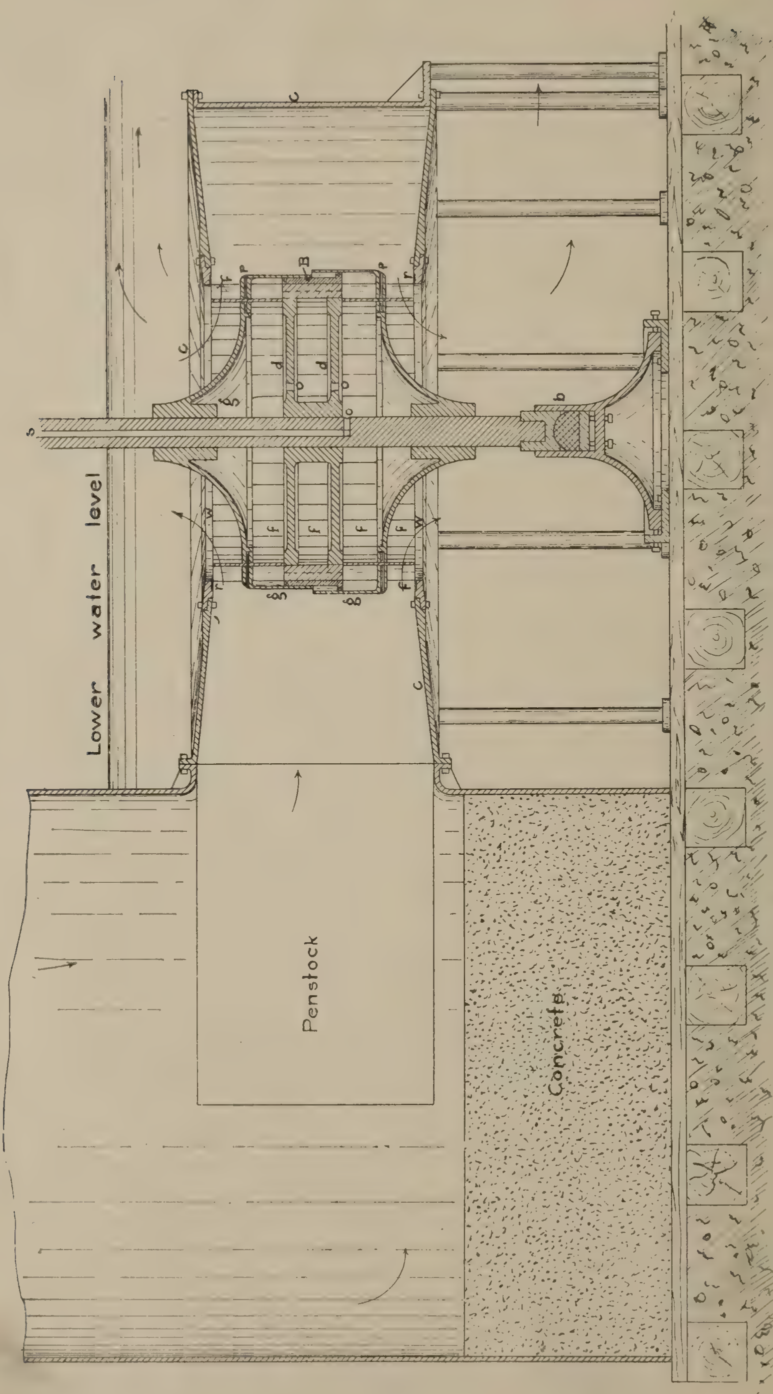


Fig. 30

and weighted as indicated, so that it follows the movement of the spindle, under the action of the revolving balls, rising when the speed diminishes, and falling when it increases. An increase of speed opens the passage leading from the upper level to the wheel; a decrease closes it. Now, in the normal running of the wheel, water is escaping from the closed chamber through the small orifices *o*, in the floats, and entering through the valve. When the valve opens wider, an increased quantity of water enters the chamber, raises the pressure therein and moves the gate to close. When the speed sud-

denly starts forward, the valve opens wide and closes the gate rapidly. When the valve closes to less than the normal opening, water escapes faster than it enters, the pressure in the chamber falls below that in the low pressure compartment, and the gate opens. The rapidity with which the gate will open when the valve is entirely closed will depend on the size and number of the openings *o*, that is, upon the quantity of water constantly wasted. The wheel under consideration has an external diameter of 5 feet and is supposed to draw some 200 cubic feet of water per second, 12,000 per minute, under a head of 20 feet. The cross-section of the closed chambers may be taken at 20 square feet. To move the gate at the rate of 12 inches in a minute would involve a loss of 20 cubic feet per minute, which in comparison with 12,000 is not worth considering. A movement at the rate of 12 inches per minute would suffice for any ordinary use of a water-wheel. A closing movement of any desired rapidity can be attained by suitable proportions of valves and passages without waste of water. To start the wheel from rest, the weighted arm is thrown into the position "to start," Fig. 29. Then the interior of the wheel is in communication with the lower level, and water from the upper level rushes through the nozzle into the pipe leading to the lower level, forming a jet pump which draws the water or air from the interior of the wheel, and opens the gate. To stop, when running, the weighted lever is thrown into the position marked "to stop." Then the valve is free from control of the regulator, and the interior of the wheel is in full communication with the upper level; the gate closes. On a low head it might be doubtful whether the wheel could be started with certainty by this method. In that case it might be advisable to temporarily connect the pipe "to upper level," with a municipal water-main, or with the fire-tank of the mill, which would, if required, make a complete vacuum in the wheel chamber. In starting the wheel after the water has been shut out of the penstock, the draft tubes and wheel chamber would be filled with air. The latter would remain filled with air after the starting of the wheel, and, as it filled with water, the air would collect at the center and obstruct the regulation of the wheel. In this case the gate would be opened far enough to admit a large volume of water and expel the air from the draft tubes, raising the water in the latter above the wheel. Then admit water from the upper level, close the gate and expel the air, which escapes through the highest orifices *o*. Then the gate can be opened without admitting air. Of course the air can be drawn out

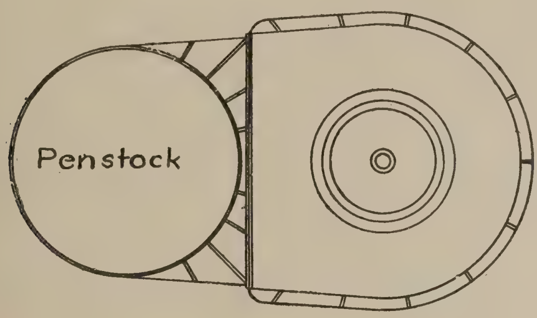


Wheel on vertical shaft. Section.

Fig. 31

by the jet pump, but this would involve opening the gate to its full width, which might not be desirable.

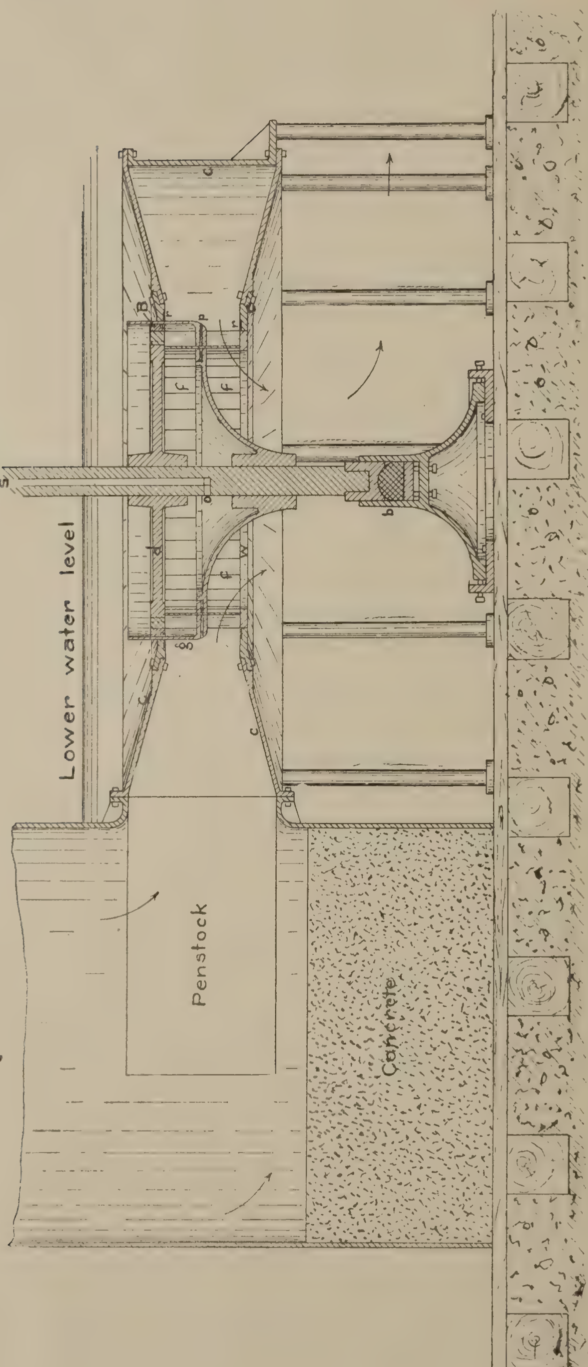
Equations 11 to 15 were deduced with reference to the regulation of the wheel by the action of centrifugal force. We will inquire what amount of force we have at disposal for the movement of the gate. The wheel under discussion is 5 feet in diameter on a head of 20 feet. This wheel takes a higher velocity than one of the common form, in which the head is partly expended in imparting the velocity through the guide passages. The exterior circumference would move



Wheel on vertical shaft – Plan

Fig. 32.

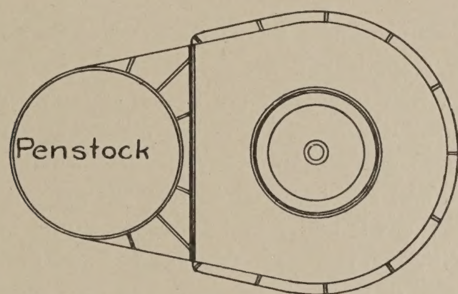
with very near the velocity due the head. When the influx of water to the wheel chamber is shut off, the internal pressure at the circumference is equal to the external pressure at the center. The internal pressure at the center is less than this by the head due the velocity, which we may call the centrifugal head. This head, in the present case, would not be less than 16 feet. The force tending to open the gate is equal to 8 feet depth of water acting on a surface of some 20 square feet — over 10,000 pounds. The force to be overcome is the friction due to the weight and packing — nothing approaching the above. Consider the most unfavorable case that could occur, 12 feet may be taken as the lowest head that a horizontal wheel would be used on, and 36′′ diameter would be about as small a wheel as would be used on such a head. The centrifugal head would not be less than 10 feet. The pressure tending to open the gate is, roughly,



Single wheel on vertical shaft. Section.

Fig. 33

$5 \times 3 \times 3 \times .7854 \times 62.5 = 2209$ lbs. For a head less than 12 feet we should employ a wheel on a vertical shaft. 6 feet may be regarded as the lowest head worth developing by water-wheels. On such a head there is seldom occasion to use a small wheel. A 5-ft. wheel on a 6-ft. head would expose to pressure something over 20 square feet for moving the gate. The centrifugal head would be about five feet. The pressure would amount to about $20 \times 2\frac{1}{2} \times 62.5 = 3125$ lbs. Of course we may conceive of a head so low and a wheel so small that this mode of regulation would be inapplicable. To meet such cases I am prepared to say that a regulator may



Single wheel on vertical shaft
Plan.

Fig. 34

be devised capable of creating a total or partial vacuum within the wheel chamber.

There is never any question as to the amount of force available for closing the gate. With full communication between the wheel chamber and the upper level, the water enters the former much faster than it can be discharged. The centrifugal head acts in concert with the static head to close the gate.

In every application of this method, the water issuing from the floats changes its direction by a right angle in leaving the wheel. This change of direction causes a pressure on the gate tending to open it. The water should not leave the wheel with a velocity of more than 6 or 7 feet per second. With 7 feet at full gate, the pressure would amount to a head of some 15 inches, diminishing to

nothing as the gate closes. No reliance can be placed on this force as aiding the opening of the gate.

The foregoing description contemplates a wheel on a horizontal shaft. Figures 31-2-3-4 show that the proposed construction is just as applicable to a wheel on a vertical shaft; 31-2 show a double wheel; 33-4 a single wheel. Neither of these presents any peculiar difficulty, or requires any special description. For a small quantity of water on a low head, a single wheel would be preferable to a double one of smaller diameter. In such case it would probably be better to let the wheel discharge upward instead of downward as indicated, in order that the weight of the gate might assist in opening.

Wheels often run under conditions to which the foregoing mode of regulation is inapplicable, as, for instance, in connection with a steam-engine, which controls the speed, and meets all variations in the demand for power. In this case, the wheel, when under no limitation as to quantity of water, runs at full gate, the regulator disconnected, and the valve set to keep the gate open. Sometimes, however, the wheel is under limitations as to the quantity of water. Natural limitations resulting from diminished flow of the stream. Legal limitation of leases and grants. In such case the gate cannot be set at any unalterable opening. It can only be left in control of the valve. It is obvious that the latter must be controlled by conditions other than the speed of the wheel.

It would be easy to point out modes of regulating the discharge, without reference to the velocity, to conform to the varying flow of a stream, to a uniform draft of water or to a uniform output of power. But such inquiries would carry us far beyond the contemplated limits of this paper.